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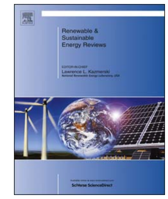

Corrosion effect of phase change materials in solar thermal energy storage application

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A R T I C L E I N F O

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A B S T R A C T

The thermal energy storage (TES) system using phase change materials (PCMs) has been studied since past three decades. PCMs are widely used in heat storage applications due to their high storage density, as well as the wide range of melting and solidifying temperatures. Nevertheless, the main disadvantage of PCMs, especially salt hydrates, is their corrosive behavior with container materials. PCMs are normally encapsulated in containers, hence the compatibility of the container materials with PCM plays an important role. As such, this paper summarizes the investigations made on the corrosion behavior of PCM in various applications, besides suggesting ways to reduce (or rectify) the effect for long term successful energy storage. Moreover, PCM-storage material interaction in the latent heat TES system is important as the issue of corrosion affects the life of the container, as well as the performance of TES. The compatibility of the most commonly used PCMs with several major container materials was reviewed and it was revealed that stainless steel has emerged as the most compatible storage container material among others. On the other hand, aluminum was found to be corrosive when it is used with salt hydrates. Nonetheless, some contradictory articles are reported that several salt hydrates demonstrated compatibility with container materials. Corrosion causes thinning of cross sectional area of materials, making it brittle thus leading to an easy collapse. This situation is even more critical mainly in large scale concentrating solar thermal power plants. Hence, with the fact that there are currently large scale power plants employing TES under operation and under construction; issues pertaining to PCM-storage material compatibility should be properly and accurately addressed. Therefore, more research work is recommended in the area of finding new eutectics and less corrosive container material(s).

1. Introduction

Energy is becoming more and more important at this present age for survival of mankind, making energy a basic need [1–3]. Since the time wheel rolled from the Stone Age, humans needed more energy to overcome their survival problems, such as cooking, heating, lighting, hunting, transportation, and so on. With evolution, fellow humans began using other forms of energies like wind and water [4,5]. Obviously, the primitive humans either directly or indirectly, used only renewable energy sources. After the industrial revolution (1700 AD), people began making use of fossil fuels (coal, natural gas, and petroleum) to satisfy their energy needs in domestic, agriculture, and transportation fields. In fact, the two broad categories of available energy resources are non-renewable energy sources (fossil fuels) and renewable energy sources (nuclear fission and fusion, hydro power, wind power, solar energy, biogas, tidal, geothermal energy, and ocean thermal energy) [2,5–7]. Non-renewable energy sources approximately satisfy 81% of energy requirement of the world, while renewable energy sources contribute only 19% [8–10]. Thus, it is obvious that non-renewable energy sources are further depleting at an alarming rate and such usages badly pollute the atmosphere by emitting CO_2 and NO_2, leading to greenhouse effect. So, the world is in dire need of finding alternate sources of energy for further use and to slow down the depletion rate of fossil fuels.

As portrayed in Table 1, there is vast potential for utilization of renewable energy as the current total utilization at 19% can further increase. This notion can definitely decrease the percentage of non-renewable energy utilization, and thereby, diminishing their associated challenges. Solar energy is a type of vast, clean, and renewable energy source. Besides, estimated to be 1.8×10^{11} MW, it is many thousand times larger compared to the total energy consumption on earth from all other energy sources. This estimation confirms that solar energy

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Table 1
Global energy potential and their current utilization of some renewable energies [11,12].

Renewable Energy sources	Global Potential TWy/Year	Global utilization TWy/Year	Challenges
Solar energy	23,000	0.0385	Intermittent, high cost of production
Wind	25–70	0.0624	Intermittent, high cost of production
Ocean Thermal Energy Conversion (OTEC) and Tides	3–11	1.248×10^{-4}	High initial cost, a few locations for installation
Biomass	2–6	1.9744	High cost of production, inefficient, requires more land
Hydro	3–4	0.608	High initial cost, reliability of supply
Geothermal	0.3–2	0.0176	High initial cost, limited to some locations, lack of skilled manpower

could supply all the energy needs of the world continuously [1]. Its cleanliness, size, and free-of-cost attributes have always sparked interest among researchers worldwide. However, the main problem related to this energy source is its dependence on availability of time (daily and seasonally). Solar energy is available only during the day, and this unavailability of the energy source during the night time increases the gap between the wasted heat availability and the utilization period. Therefore, it is deemed necessary to identify an efficient way to store the thermal energy for later usage.

In addition, developing energy storage methods has equal importance to finding new energy source. The challenge, nonetheless, only starts when storing energy in its suitable form and converting it to the required form. Storing energy reduces the wastage of plenty of available energy that can be used later when it is needed. Energy storage in the field of power generation increases efficiency and leads to energy conservation [13–17]. Moreover, energy storage (ES) has its own impact on modern technology when it meets energy demand. Thus, the ES systems contribute significantly in utility (charging ES system using inexpensive base load electricity), industry (heat released during various industrial processes are stored in ES), co-generation (electricity and heat are produced together and stored), wind and run-of–river hydro (stored as electricity when available throughout the year), and solar energy (storing solar energy during sunny days at all time) applications [18,19].

In fact, several methods of ES systems have been continuously utilized in different areas, such as mechanical energy storage, chemical energy storage, biological storage, magnetic storage, and thermal energy storage (TES). Mechanical energy storage systems are comprised of three types: the hydro storage, the compressed air storage, and the flywheel energy storage systems. In the hydro storage, water is pumped from the river and stored in the reservoir at a higher level, whereby the water in the reservoir can be used to generate electricity if there is need for energy. Meanwhile, in the compressed air ES system, air is compressed using conventional gas turbine and stored in man–made or natural caverns, used oil or gas wells, or porous rock formations [20]. When energy need arises, electricity is generated using the similar method employed for hydro storage. On the other hand, the flywheel stores rotational kinetic energy and used for transportation, as well as electricity production [21]. Besides, reversible chemical reaction can be used to store energy. The absorption and release of heat during chemical reaction confirms its application in the field of TES. Additionally, energy stored in batteries is called electrochemical storage. In batteries, energy is stored in the form of chemical energy, but released in the form of electrical energy, such as lead-sulphuric acid battery [22]. Biological storage is another form of storing energy in chemical form using biological processes [23,24]. At absolute zero temperature, certain metals have no resistance against electricity, which helps to store direct current (DC) in the magnetic field, experiences energy loss during its conversion to alternating current (AC). Energy storage is also possible by using hydrogen. Hydrogen can be produced via electrolysis and stored as chemical energy. In fact, hydrogen can be used to generate electricity in fuel engines [22,25–28]. Even though many types of ES systems are available, they are limited by cost, volume of storage, low density, and limited efficiency [22]. Furthermore, the world needs low cost, environmental-friendly, and abundant source with comfortable storage facilities. As for solar thermal energy utilization, the most common energy storage system is the TES system that collects the excess heat energy during sunshine hours and stores it in the form of thermal energy for night usage [18].

The two commonly used TES methods are sensible heat storage (SHS) and latent heat storage. ES in the sensible heat method is based on the temperature change that takes place in the material. Meanwhile, in the liquid based systems, water is used as the heat storage material, whereas rock bed is employed in air based system [18,29]. Besides, sensible heat is cheaper compared to latent heat storage (LHS); but its energy density is lower, thus requires bigger storage volume and its usage is limited by the gliding discharge temperature [18]. Unlike the SHS, the LHS, which is also called PCM, changes its phase at a particular temperature (melting temperature), in which further heating allows the heat energy to be stored in the phase change. However, the heat dissipates when it is cooled again. Latent heat storage system has higher storage density compared to sensible heat storage system of about five to ten times. The volume of storage of LHS is two times lower than SHS [30]. LHS has materials with wide range of melting temperature so, can be used for all type of applications. Moreover, the problems faced during latent heat storage methods are low thermal conductivity, density change, stability of properties during long term cycling, phase segregation, sub cooling [18], and corrosion [31]. Nonetheless, all these problems can be solved using appropriate methods. Various performance factors of different TES is given in Table 2.

The main challenge faced in the TES by the LTS method is the incompatibility of phase changing materials with the storage containers. Moreover, only a handful studies have looked into the corrosion effect of phase change material on the storage containers. This review paper mainly concentrates in this area. Besides, no complete data is available in relation to the list of PCM and compatible materials that can be used for storage containers. This review paper presents the work performed on that task as well. As such, this review paper consists of four sections. Section 1 discusses the different kinds of energy sources and the methods of storing them. This section gives information about the importance of solar energy and the methods of storing it. The problems faced during the storage of solar energy using PCM are listed in this section as well. Next, Section 2 details the types of PCM, their classification, and their application areas. Meanwhile, Section 3 discusses the corrosion effect of PCM on storage container and heat transfer fins. Finally, the concluding remark is provided in Section 4.

2. Different phase change materials (PCM) used in thermal energy storage (TES)

2.1. Classification of PCM

Phase change materials are substances that undergo phase change during the absorption/release of energy from/to the surroundings. The temperature of the material remains constant until the phase changing process is complete, thus a large amount of energy is stored.